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Art. IV.—The Silurian Rocks of the Studley Park District.

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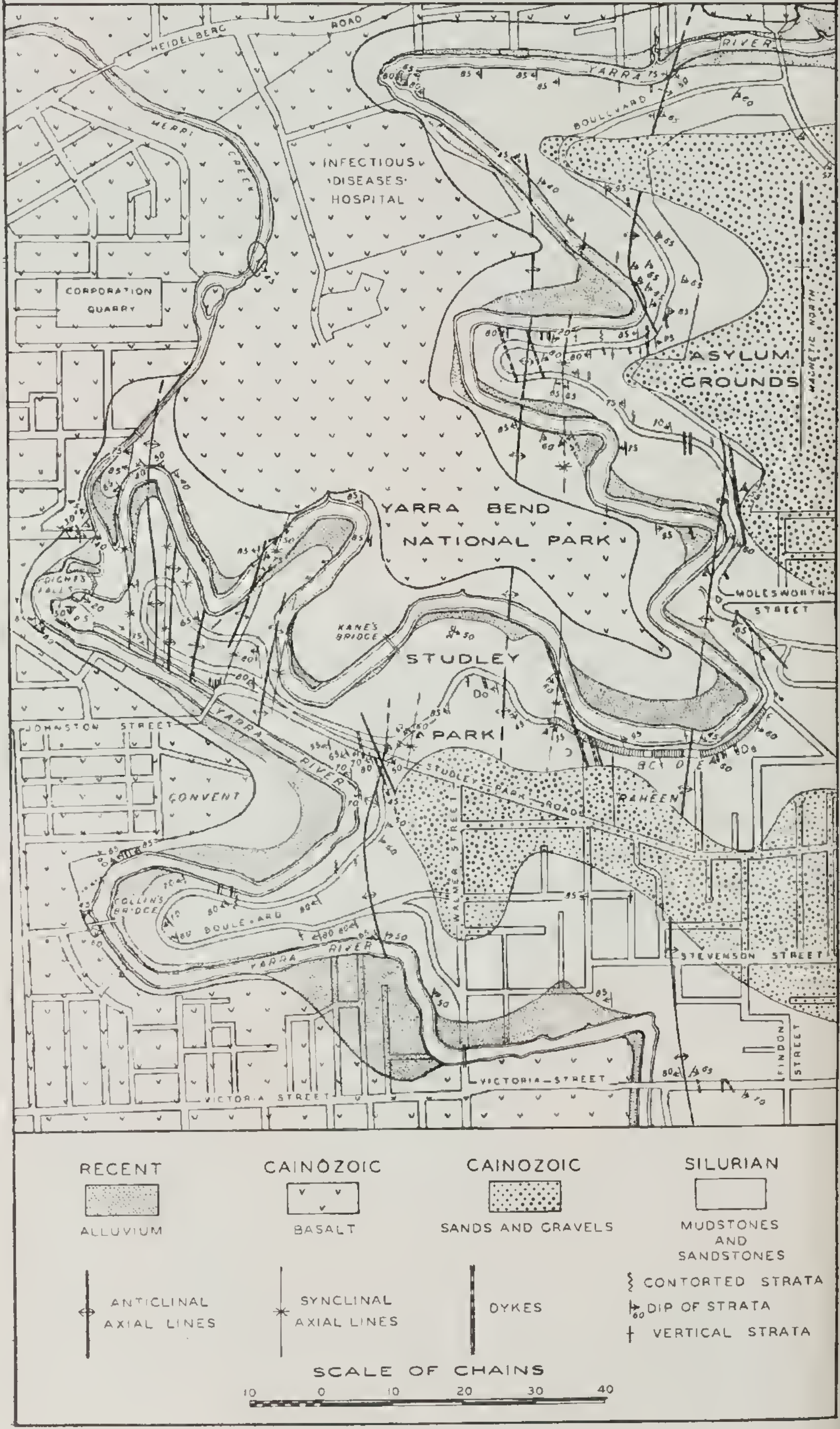
Contents.

Introduction.

The construction of the Yarra Boulevard between Studley Park and Fairfield recently afforded an excellent series of road sections, which the author took the opportunity of investigating while constructional work was in progress, in order to elucidate the complex folding, faulting, and other structural features exhibited by the Silurian strata that form the bedrock of the district. The sections available for detailed study, including the river banks and excavations for roads and tracks, amounted to upwards of 12 miles, although the Silurian rocks occupy only about one square mile in the area mapped. This area is included in quarter-sheet No. 1, N.E. (Melbourne), of the Geological Survey of Victoria, and also in Miss Nicholls' map of the axial lines of folds in the Silurian rocks in the eastern suburbs of Melbourne (Nicholls, 1930). The data available to the present author indicate that the structural information as to dips, strikes, and folds shown on both these maps is unreliable, but only minor changes have had to be made in the geological boundaries on the quarter-sheet. In spite of careful and repeated examination of every outcrop and section, however, it was found impracticable to map all the minor folds, especially in the "crush zone" between Johnston Street Bridge and Dight's Falls. In general, the chief axial lines shown on the map (fig. 1) have been located accurately in the field over considerable distances, though in a few places the delineation of major structures is still somewhat uncertain. For information concerning the general geology of the district the paper by Hauser (1923) may be consulted, the present contribution being concerned only with the Silurian rocks, and the dyke intrusions that penetrate them.

GEOLOGICAL MAP OF THE STUDLEY PARK DISTRICT



Palaeontology.

Fossils have previously been obtained from the track to the Pumping Station (*P.S.* on the map, near Dight's Falls) and also from the spur above the Falls. Hauser listed *Monograptus* sp., cf. *Streptelasma, Camarotoechia decemplicata, Chonetes melbournensis,* and *Loxonema* sp. from these localities, and Jones (1927) recorded *Monograptus chimaera, M. roemeri, M. colonus,* and *M. varians* from the track to the Pumping Station. Harris and Thomas (1937) determined *M. crinitus* from this section, and Withers and Keble (1934) described a new species of brittle-star, *Furcaster bakeri,* in a collection made by Mr. G. Baker from the loop in the Boulevard north of Johnston Street Bridge. The Rev. E. D. Gill has kindly examined Mr. Baker's collection and also fragmentary shelly fossils obtained by me from the foundations of a pylon north-west of Victoria Bridge, from the northerly extension of these beds on Studley Park Road, and from sewerage excavations in Kevin Street; he has supplied the following list of forms so far identified from the Studley Park district:

PLANTAE:	*Bythotrephis divaricata* Kidston, *B. tenuis* Hall.
COELENTERATA:	cf. *Streptelasma, Monograptus chimaera* (Barrande), *M. colonus* (Barrande), *M. roemeri* (Barrande), *M. varians* Wood, *M. crinitus* Wood.
ANNELIDA:	*Keilorites* sp.
ARACHNIDA:	*Hemiaspis tunnecliffei* Chapman.
MOLLUSCA:	*Pleurotomaria* sp., *Loxonema* sp., *Hyolithes* sp.
BRACHIOPODA:	*Chonetes melbournensis* Chapman, *Nucleospira australis* McCoy, *Plagiorhyncha decemplicato* (Sowerby), *Rhynchatrema liopleura* McCoy. *Spirifer* sp. nov. (?).
ECHINODERMATA:	*Furcaster bakeri* Withers and Keble, *Sturtzura brisingoides* (Gregory), Crinoid stem joints.

In spite of careful searching along the excellent sections north of the tunnel beneath Studley Park road, no fossils have been obtained in this part of the area, and the palaeontological data now available necessitate no change either in the earlier reference of the strata to the Melbournian Series, or their correlation with the *M. nilssoni* Zone of the Ludlovian of Great Britain (see Jones, 1927; Chapman and Thomas, 1935).

Folding.

Miss Nicholls (1930) indicated a synclinal axial line immediately to the east of Dight's Falls, the "Studley Park" anticline just over half a mile further east and extending across the whole of the area dealt with in this paper, and a syncline at the bend in the Yarra River east of "Raheen." As may be seen by inspection of figure 1 and Miss Nicholls' map, the generalizations made by her in extrapolating axial lines from a few observed field apices have not been borne out by more detailed work on the excellent exposures that were available to the present author. The axial lines shown by Miss Nicholls trend N. 25° W., whereas actually the trend ranges between N. 15° W. and N. 5° W. in the north of the area, to N. 10° E. in the south. Thus the Victoria Bridge anticline, which as previously represented appeared to deviate notably from the general trend, is actually one of the major folds of the district, and fits into the tectonic framework in a normal manner (cf. Nicholls, 1930, p. 132).

The zone of closely packed minor folds near Johnston Street Bridge is sharply delimited on the east, terminating near the entrance to the Boulevard from Studley Park Road. The southerly continuation of this zone is found north of Collins' Bridge, but it is obscured further south, and also in the north, by late Cainozoic basalt flows. The formation of these complex minor folds is undoubtedly connected with the presence of massive sandstones at Dight's Falls, as was recognized by Miss Nicholls. Most of these minor folds are approximately congruous drag folds (see Hills, 1940, p. 90) ranging in strike from 360° to 22°, and pitching south at angles up to 15°. In the river cliff opposite Deep Rock Pool, the strongly disharmonic nature of the minor folding in this section is evident. Miss Nicholls has given two alternative sections to illustrate the structure near Dight's Falls, both based on the assumption that the sandstones at the Falls are not represented in the section along the track to the Pumping Station. These interpretations are, however, open to doubt because of a misreading of the dip at the Falls, which is south-easterly, and not north-easterly as recorded by her. The present author agrees that the structure is in general synclinal, but concludes that the sandstones at the Falls are represented in the west-dipping limb at the western end of the track to the Pumping Station, and that, as is usual in the district, the pitch is to the south, and not to the north, as was suggested (cf. Nicholls, 1930, pp. 131-2).

The folds are of the zig-zag type, asymmetrical, listing towards the east in depth, with vertical or slightly overturned strata in many of the west-dipping limbs, and dips of about 60°–65° commonly occurring in the east-dipping limbs. Throughout the area the pitch is southerly, although in the north many observed fold apices are horizontal. The southerly pitches themselves show a remarkable range. Thus the Victoria Bridge anticline, on the River north of "Raheen," pitches at 30°, the syncline east of the tunnel under Studley Park Road pitches at 50°, and a drag fold in the river cliff south of the Convent pitches at 90°, the adjacent strata themselves dipping at this angle (fig. 2).

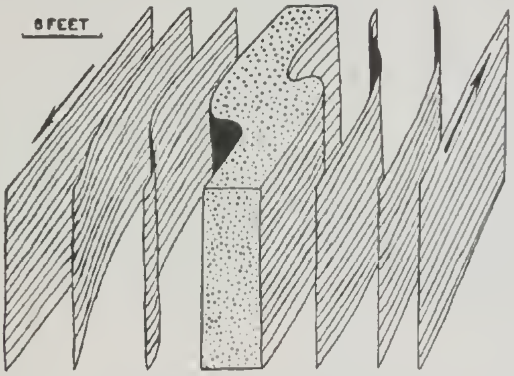


Fig. 2.—Incongruous drag fold pitching at 90°. River cliff north of Convent.

Numerous other examples of small drag-folds pitching at high angles occur in the district, where, as is also shown by slickensides, considerable bedding-plane slip in directions ranging from parallelism with the dip to parallelism with the strike of the folded strata has gone on. The apices of the resultant drag-folds pitch in a southerly sense at angles ranging from 0° to 90°. Drag-folds caused by horizontal shearing movements in already highly inclined strata have been termed "independent" by Derry (1939),

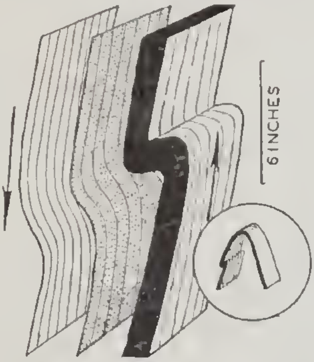


Fig. 3.—Incongruous drag fold, E. end of Victoria Bridge Cutting. Inset in circle shows diagrammatically the relation of the drag fold to the Victoria Bridge Anticline.

signifying that their development resulted from forces independent of those causing the main folding. If, however, there was a horizontal shearing couple involved in the folding, even locally (see Hills, 1940, p. 58), horizontal bedding-plane slip would in all probability take place after the beds were folded, leading to the development of the so-called "independent" drag folds. The present author therefore prefers to term such drag-folds "incongruous," signifying that they do not agree with Pumpelly's Rule, but not implying that they are necessarily of a distinct and separate origin from the major folding.

Near the eastern end of the Victoria Bridge cutting, on the south side, there is a small drag-fold (fig. 3) that is incongruous in yet another sense, for, as shown in the inset in figure 3, it apparently indicates movement of the upper strata away from the anticlinal axis, and not towards it as is usual. This arrangement is the same as was observed by Bain (1931) in the limbs of anticlines in limestone, the drag-folds ("flowage folds") being caused by the slipping of strata down the anticlinal limbs, away from the fold axis. The same explanation may hold for the present example.

Faulting.

As has been remarked by Hauser (1923) and Miss Nicholls (1930) reverse faults are common in the Studley Park district, but the surprisingly large number of such faults present has only been revealed by the new sections, in which a considerable number of normal faults is also shown. The dip and strike of 100 faults could actually be measured, and frequency diagrams representing the direction of dip of these faults have been prepared (fig. 4). There are, however, innumerable faults with a slip of the order of an inch, that were not measured, and many others with greater amounts of slip, whose strike and dip could not be determined. The fact that westerly-dipping fault planes are by far the commonest is clearly brought out by the frequency diagrams, and is indeed obvious in the field (see profiles, figs. 5 and 6). The average angle of dip of the fault planes is 50°, and, over the whole area, the average strike is 170°.

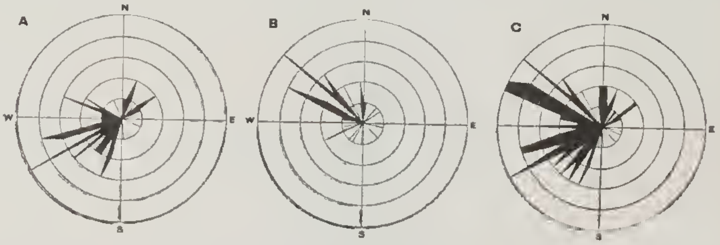


Fig. 4.—Frequency diagrams of direction of dip of 100 fault planes along the Yarra Boulevard. *A*, southern area—between *A* on profile *AB*, and Molesworth St.; *B*, northern area—north of Molesworth St.; *C*, composite diagram of all faults. Interval for bearings, 5 degrees; circles unit distance apart—one fault per circle.

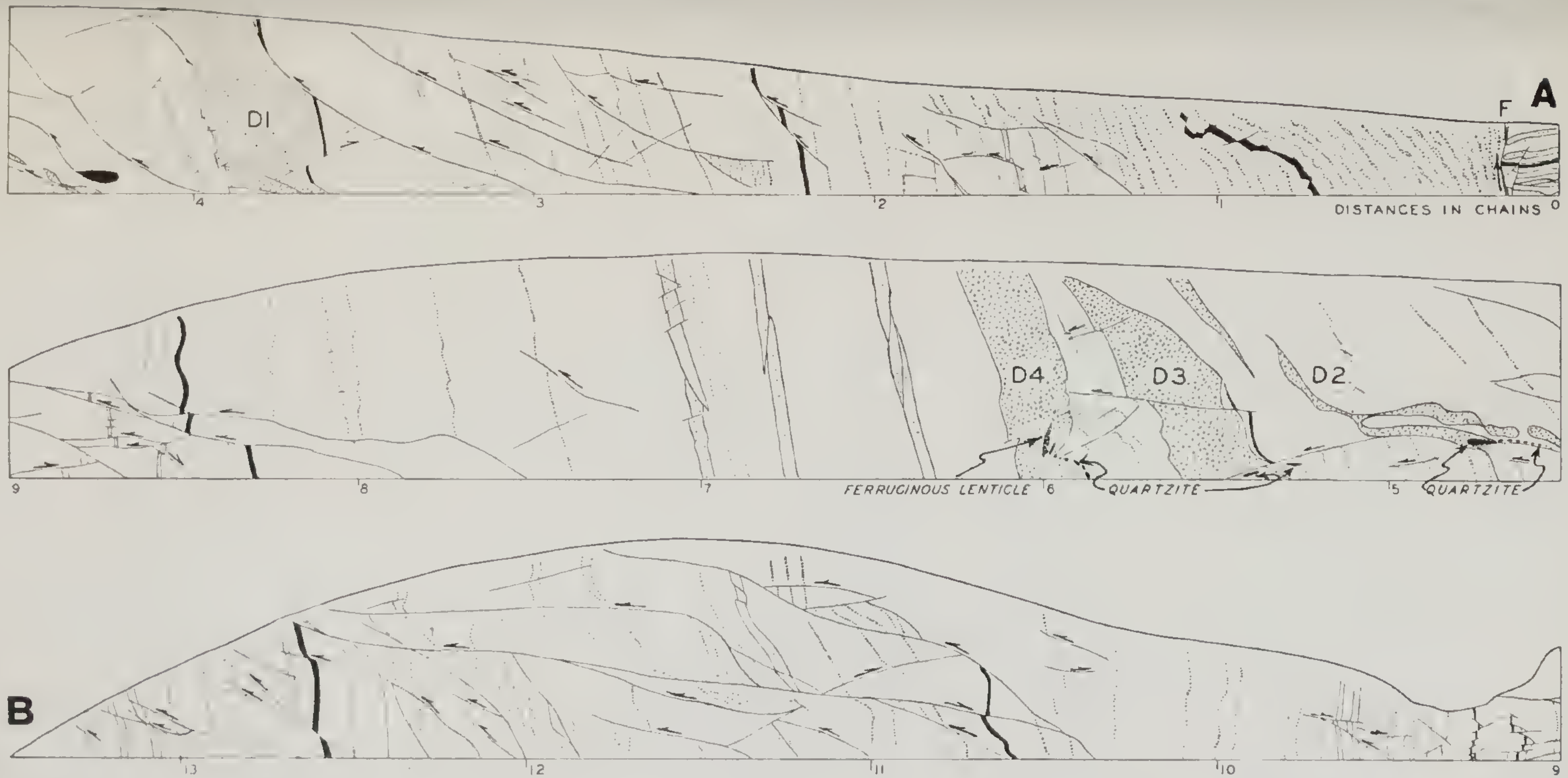


Fig. 5.—Profile along the Yarra Boulevard: location shown on map (fig. 1) by cross-lining of Boulevard between *A* and *B*. Key strata shown somewhat diagrammatically by conventional symbols, e.g., solid black, dots, or dots between lines. Direction or relative movement along faults shown by arrows. *F*, fault shown in detail in fig. 7. D1–4, dykes.

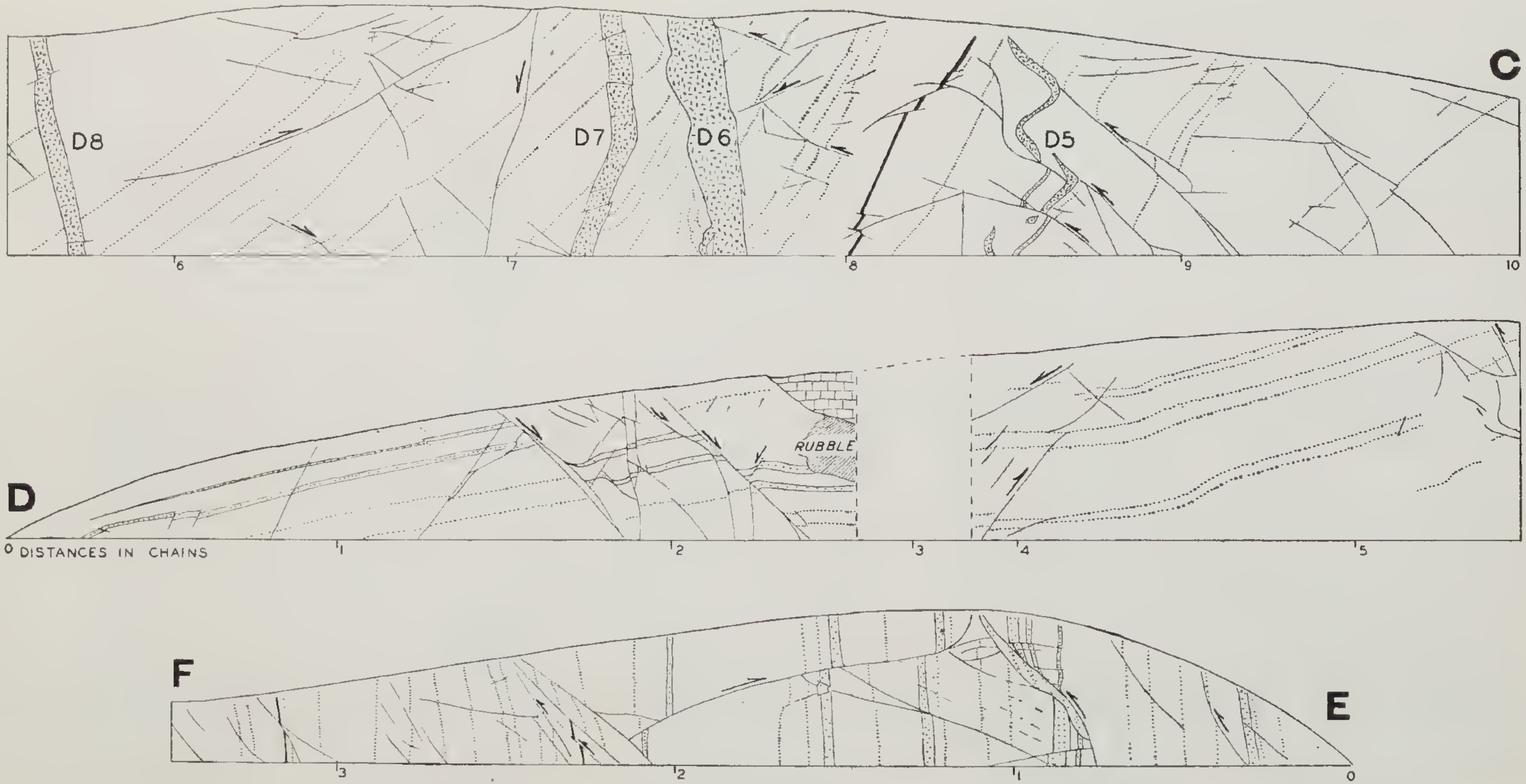


Fig. 6.—Profiles along the Yarra Boulevard: location indicated on map by cross-lining between *CD* and *EF*.

NORMAL FAULTS.

The fault labelled F in figure 5 near A, brings sheared incompetent mudstones and thin sandstones against more massive sandstones on the west. The latter show apparent "drag" both upwards and downwards, so that the direction of relative movement of the blocks is not immediately obvious. The displacement is, however, clearly indicated by the pinnate shearing planes (S, fig. 7) in the incompetent beds adjacent to the fault plane.

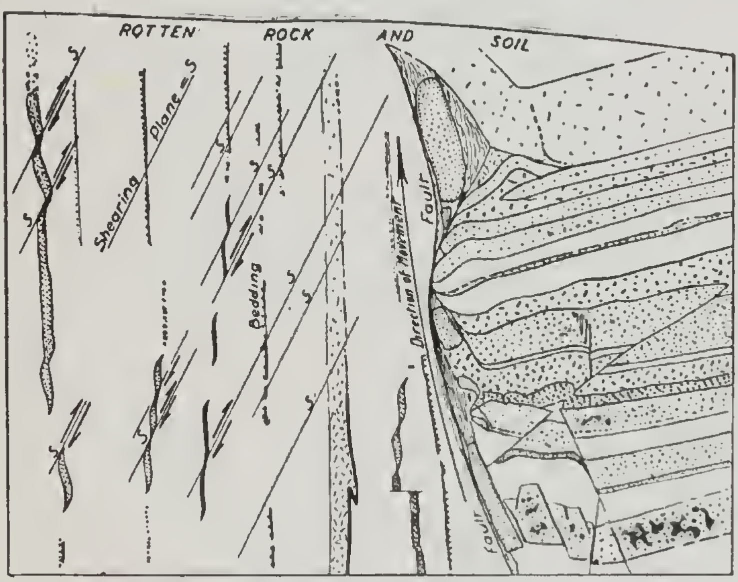


FIG. 7.—Sketch showing the structural features adjacent to fault *F* (fig. 5). The direction of movement along the fault is indicated by the downward opening of the acute angle between the fault plane and the shearing planes *S*. Length of section, 18 feet. West on right.

By analogy with the experiments of Riedel (1929) it is clear that the relative movement of the eastern block was upwards, the western downwards, this being indicated by the attitude of the pinnate shearing planes in relation to the fault plane. If the fault actually hades towards the west in depth, as it does in the section exposed, then it is a normal fault. Other normal faults occur near the 2 chain mark on profile CD (fig. 6).

REVERSE FAULTS.

The great majority of the faults in the district are reverse, being shear thrusts (Hills, 1940, p. 116) that have been formed in already folded strata (see profiles, figs. 5 and 6). The commencement and termination of some of these faults may be seen in the sections, the general arrangement being as shown in figure 8. In almost every case, the strata at the end of a shear thrust are flexed, then the flexure is broken through, and the amount of slip increases progressively along the fault, until it reaches a maximum, after which the slip decreases until the strata again are merely flexed and not faulted. Where there is actual separation of the strata, the so-called "drag," which may be used to determine the direction of relative displacement of the fault blocks, is seen to be the result of the shearing through of the preliminary flexure, and not due to friction along the fault plane. In many instances, the flexing alone is developed, along a plane that would, if more displacement had occurred, have become a fault. It is proposed to designate such structures as "shear flexures." In massive strata, the "drag" effect results from a small amount of preliminary shear flexing, combined with numerous small displacements along subsidiary fracture planes (see top of profile EF above the 1 chain mark; also Pl. V., fig. 1).

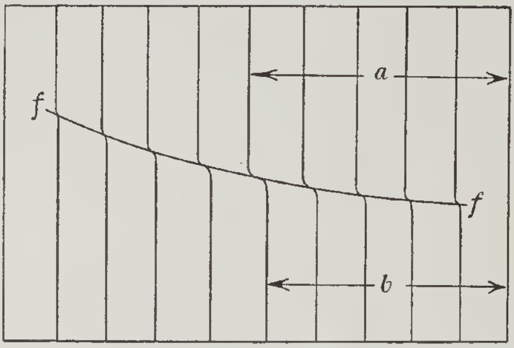


FIG. 8.—Diagram showing the mode of development of shear thrusts at Studley Park. Note the preliminary shear flexing at the ends of the fault plane *f f*, and the increasing slip towards the centre of the fault. Measured examples show *a* : *b* as 20 : 19.

High-angle reverse faults, many of which are closely connected with individual folds, are common in the "crush zone" near Dight's Falls. (See fig. 10A: also Section B in Nicholls, 1930, p. 134.)

BEDDING FAULTS.

In all sections, there is evidence of marked slipping of strata along bedding planes. The existence of definite bedding faults, as distinct from bedding-plane slip consequent upon the folding mechanisms, and from pre-tectonic sliding movements which will be discussed below, is indicated by the passage of thrust-fault planes into bedding planes in many localities.

Jointing.

Complex jointing is present throughout the area, and it is not always possible to decide upon the origin of particular joints observed in the field. It is clear, however, that the majority of the joints, especially those that may be seen to traverse several adjacent beds, are shear joints, cognate with the reverse and normal faults. This is shown by the parallelism of joint and fault planes, and the complete gradation observable between faults and joints, as regards the amount of slip (see Pl. V., fig. 2). Many fault planes indeed commence as shear joints, and in other instances parallel shearing planes include examples of both faults and shear joints, the slip along the latter not being of sufficient magnitude to enable it to be determined. In profile CD, between the 1 and 2 chain marks, a clear example showing two intersecting sets of shear joints, each set parallel to a fault plane, suggests that other examples of intersecting joint sets, which are especially characteristic of the sandstone strata in the Melbourne district, have a similar origin as incipient complementary shearing planes of tectonic origin. It is probable, however, that many of the joints in both sandstones and mudstones are not of tectonic origin, but were produced by weathering. Thus in several instances successive sandstone beds are independently jointed, each bed exhibiting intersecting joint sets, normal to the bedding planes, and enclosing a different dihedral angle in each stratum. The arrangement, which is shown diagrammatically in figure 9, and the fact that on close study the joint planes appear to be open gashes, suggest that the joints in the sandstones are caused by expansion of interbedded mudstones in the zone of weathering, due both to mineralogical changes and to swelling of the clay fraction on wetting. Such expansion would have been transmitted to the sandstones owing to the adherence of the strata with one another, and it is suggested that the joints in the sandstones developed as a result. Expansion of the sandstones themselves would also have contributed to the process, and removal of the load of superincumbent rock by erosion may also have played a part in the development of jointing in the superficial rocks.

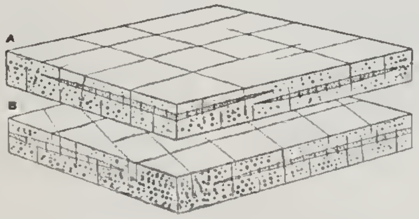


Fig. 9.—Diagram showing the nature of intersecting joints sets in adjacent sandstone strata, probably due to weathering. *A* and *B*, laminated sandstones with interbedded lenticles of structureless sandstone. In *A* joints intersect at 60°; in *B* at 90°.

Cleavage.

Regional cleavage is not developed in the area, in spite of the close folding to which the rocks have been subjected. At three localities, however, there is a local development. In the anticline along the track to the Pumping Station (3 chains from the commencement of the section near the bridge—see fig. 10) a patch of mudstone squeezed along the fold limb near the apex shows a definite cleavage over an area of a few square inches. The cleavage planes are curved, as with typical fracture cleavage in such an environment, and under the microscope they are seen to be rather indistinct shearing surfaces, associated with the minute shear flexures typical of slip-strain cleavage. Cleavage is also present in mudstones in an exposure of a few square yards in the outfall of the Riley Street drain, where there is intense brecciation of sandstones and flowage of mudstones in a zone

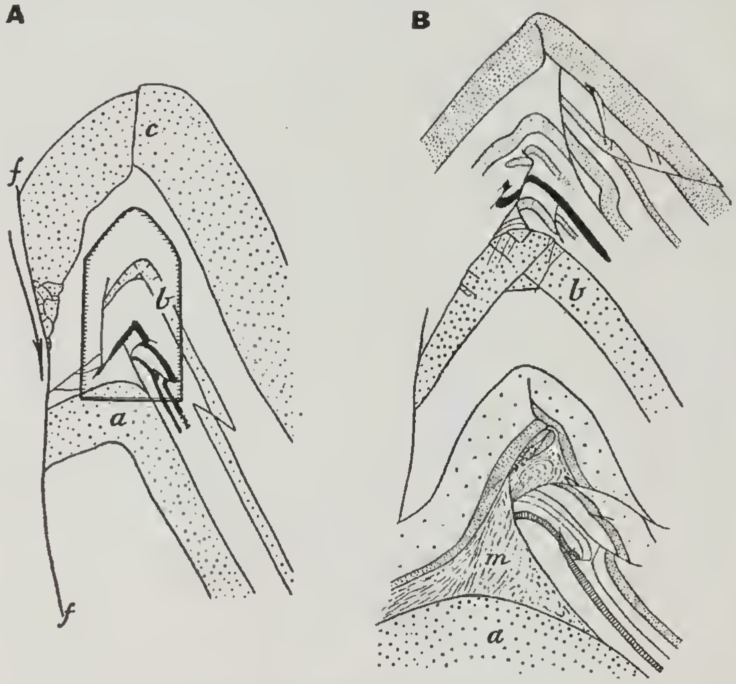


Fig. 10.—*A*. Anticline at 3 chains from the commencement of the section near the Bridge, on the track to Pumping Station. Height of section, 8 feet. The shaded area between the massive sandstones *a* and *c* is represented in detail in Fig. 10*B*. See also photograph in Nicholls, 1930, Pl. X., Fig. 1, *f f*, fault.

B. Detail between beds *a* and *c* in *A*. Height of section, 3 feet. Note the evidence of flow in mudstones *m*, fracturing of sandstone *b* at the fold apex, and minor shearing and flexing of sandstone layers interbedded in mudstones, the displacements indicating flowage towards the fold apex, parallel to the major bedding planes.

of shearing. The most extensive occurrence of cleavage is, however, adjacent to dyke D8 (see profile CD, fig. 6). There, sandstones and mudstones are both cleaved, though the cleavage is better developed in the mudstones. It is parallel to the dyke walls, following irregularities in them, and is well developed for a distance of 5 yards from the dyke on the western side, becoming indistinguishable at 10 yards. On the east cleavage is developed for only one yard from the contact. The strata have been metamorphosed for a distance of about one yard along each wall of the dyke, three zones being distinguishable. Adjacent to the dyke the strata have been rendered soft for about 6 inches. Then there is a zone about one foot to two feet wide in which both sandstones and mudstones have been hardened, and finally the outer zone, up to two feet wide, has been leached to a pale cream colour.

The persistence of the cleavage into the hardened zone indicates that the formation of cleavage antedated the metamorphism of the strata, but there can be no doubt that the cleavage bears some relationship to the presence of the dyke. The latter is unusual in that it contains numerous cognate and foreign xenoliths. Its western face is polished and slickensided, while its eastern is crumbly and shows no evidence of movement. The western face also shows undulations and steps, indicating that it is a fault plane, along which the adjacent country rock on the west has been displaced (relatively) downwards. Under the microscope the cleavage planes in the hardened rock of the zone of metamorphism show no evidence of shear, and their nature could not be satisfactorily elucidated. Finally, it may be noted that mudstone beds are shattered in the hardened zone, though showing regular cleavage without marked shattering further from the dyke, and that near the bottom of the dyke in the road section the metamorphic zones show a clear displacement of about a foot, along a bedding fault.

The interpretation of these data is as follows:—

1. There has been post-solidification faulting along the western contact wall of the dyke.

2. Minor post-metamorphic faulting has taken place along planes intersecting the dyke.

3. The cleavage antedated the final stages of the metamorphic processes.

4. The parallelism of the cleavage with irregularities in the dyke walls, the presence of only one set of cleavage planes, which traverse sandstones and mudstones alike, and the absence of shear flexures on cleavage planes, indicate that the cleavage is not tectonic in origin.

Since it is extremely improbable that such a local cleavage zone should have been developed except in relation to the dyke intrusion, while on the other hand such cleavage zones are absent from all the other dykes in the district, the conclusion is reached that the cleavage resulted from volume changes in the country rock as a result of the permeation through it of solutions of magmatic origin. The possibility that the cleavage resulted from the compression of the strata as a result of the forcible injection of the dyke cannot, however, be rigidly excluded.

Ultimately, the magmatic solutions caused the metamorphism that is now preserved, but the final production of the metamorphic zones post-dated the development of cleavage. It will now be clear that the cleavage along this dyke has no bearing on the question as to whether or not regional compressive forces operated after the dyke intrusions.

Dyke Intrusions.

Numerous narrow dykes, ranging from a foot or even less to about 10 feet wide, traverse the Silurian rocks (Pl. V., figs. 3 and 4). In no place do they intersect the overlying Cainozoic sands and gravels, but nevertheless their age has been regarded as Tertiary, because a fresh dyke at South Yarra proved to be a lamprophyre, and the lamprophyric dykes of the Midlands goldfields are usually regarded as Tertiary (Edwards, 1934). It is not proposed to discuss herein the general question of the age of the dyke and other minor intrusions throughout the Melbourne district or farther afield, but it may be noted that in addition to lamprophyric types (one of which occurs at the corner of Church-street and Alexandra-avenue) there are acid dykes and minor granitoid intrusions in the South Yarra district. These acid rocks are almost certainly of epi-Devonian or Carboniferous age, and there are, therefore, no *a priori* grounds for assuming that all or any of the dykes at Studley Park are Cainozoic.

Most of the dykes are too thoroughly decomposed to permit their original petrological nature to be determined. Some are now plastic clays, white or cream in colour, others are of a very "short" powdery texture, with a residue of fine gritty particles. The dyke labelled Do on the map (west of "Raheen") is, however, fresh enough for study. In hand specimen the rock is seen to consist of phenocrysts of simply twinned white felspar up to $\frac{1}{4}$ in. across and $\frac{1}{2}$ in. long, together with small biotite flakes up to $\frac{1}{8}$ in. across (but generally less), set in a mottled ground mass that has a lustrous appearance owing to the presence of numerous small felspar laths. Under the microscope (see fig. 11A) the phenocrysts are seen to be anorthoclase, often in characteristic aggregates resembling glomero-porphyritic texture. A phenocryst of oligoclase, showing very narrow albite twinning lamellae, and rimmed with anorthoclase, occurs in one section

A few red-brown biotite plates are present, and also small pseudomorphs of a chloritic or serpentinous nature, obviously after pyroxene. The crystal habit of these pseudomorphs and the measurement of apparent interfacial angles suggest that the original pyroxene may perhaps have been aegirine. The ground mass is trachytic, with close-packed laths of fresh sanidine, numerous specks of weathered iron ores, and an interstitial green chloritic or serpentinous base. This rock is an anorthoclase trachyte, resembling extremely closely the anorthoclase trachytes of the Macedon district. Actually, the closest resemblance, mineralogically and texturally, is with the so-called "solvsbergites" of that district, which, in a strict petrological sense, are anorthoclase trachytes.

The nature of the more decomposed dykes at Studley Park could not be made out so clearly, but in D2 there are some felspar laths, a few biotite flakes, and numerous limonite pseudomorphs after a ferro-magnesian mineral. D3 is similar to D2, but contains also clots of cream amorphous material. The limonite-rich lenticle in D4 (see profile AB, fig. 5) contains phenocrysts of sanidine or soda-sanidine, and there are also traces of sanidine laths in the groundmass, as well as of small altered phenocrysts of a ferro-magnesian mineral. The dyke D8, adjacent to which cleavage is developed, is itself completely decomposed, but it contains numerous xenoliths. Two different types of xenoliths, one a pure white felspathic type, another resembling a graphic granite in hand specimen, were fresh enough to be sectioned.

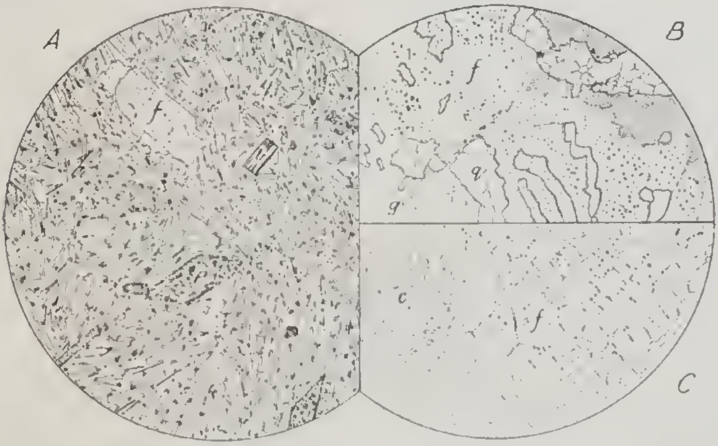


FIG. 11.—*A*. "Solvsbergite" (anorthoclase trachyte) dyke. *Do* (see Map). *f*, anorthoclase; *b*, biotite; *p*, pseudomorph after pyroxene.

B. Graphic soda-granite xenolith in dyke D8. *f*, soda-orthoclase; *q* quartz; *g*, granular zone along shearing plane. Close stippling indicates fine-grained felspathic material, possibly injected into the graphic soda-granite.

C. Felspathic xenolith in dyke D8. *f*, sub-rectangular anorthoclase crystals; *c*, "clot" containing sanidine laths. All x 8.

The felspathic type (fig. 11c) is a snow-white saccharoidal rock, consisting entirely of a mass of anorthoclase crystals with an aplitic texture. It is related to the lestiwarites of Norway and Finland, which are aplites of the alkali syenite series (Johannsen, 1937, Vol. III., pp. 25-6). Rounded clots of finer grained material, containing minute alkali-felspar laths, are also present.

The other xenolith (fig. 11B) consists of an intergrowth of quartz and alkali felspar, the latter probably a cryptoperthitic soda-orthoclase. Originally the intergrowth appears to have been graphic, but granulation and recrystallization have affected both quartz and felspar, the former showing embayment.

It will be clear from the above descriptions that an alkaline suite of rocks is represented among the dykes, and the general similarity with the Cainozoic trachytes and "solvsbergites" of the Macedon district is obvious. The petrological evidence therefore strongly suggests that the Studley Park dykes are also Cainozoic. In view of this, it is important to investigate the relationship between the dykes and the faults, especially the reverse faults, in the district. As may be seen by inspection of profiles AB and CD (figs. 5 and 6), dykes D1, D3, and D8 have apparently been displaced by later faults. Dyke D5 is, however, clearly post-faulting, as it follows the bedding and the fault planes alternately (Plate V., fig. 3). The question arises as to whether the apparent displacements of the other faults may perhaps be due to the dykes pushing apart already faulted strata. Owing to the advanced state of decomposition of the dykes, and the absence of metamorphic effects along them (except for D8) it is not possible to investigate displacements of chilled borders or metamorphic aureoles, which would yield definite evidence with regard to the relative age of the faults and dykes. Where dykes have apparently been faulted (e.g., D1, D3, and D4), it is perhaps significant that certain of the faults appear to die away within the dykes. If the dykes were unaltered when faulted, this would not be expected, owing to the incompressible nature of the fresh igneous rock. The definite evidence that is available (for D5 and D8) indicates that faulting occurred both before and after the dyke intrusions, the only certain post-dyke displacement being, however, of small amount.

In the ferruginous sands and gravels exposed in the new pit south-east of the tunnel under Studley Park-road, there are angular pebbles of clay, closely resembling that of the decomposed dykes. As remarked above, the latter do not cut the sands, whose age is certainly Cainozoic, but of what period is uncertain. They must, however, have ante-dated the Newer Volcanic lavas of the Yarra Valley by a considerable period of time, and are usually regarded as Lower Pliocene. The dykes are themselves considerably older than these sands and gravels, and almost certainly are pre-Pliocene.

Structural Details in the Silurian Rocks.

Primary Structures.

The lithological types represented in the district include massive resistant sandstones, softer current-bedded sandstones showing "drift-bedding" according to Sorby's nomenclature (1908) or the "complete curve of current bedding" according to Bailey (1930), together with sandy and fine-grained mudstones. Usually there is a rapid alternation of thin sandy and muddy beds, but in places mudstones are subordinate, as near Dight's Falls, while elsewhere sandstones are locally subordinate.

Many of the massive sandstone strata exhibit an indistinct graded bedding, and the tops of current-bedded sandstones typically show ripple or current-mark. Typical current ripples with parallel crests are rare, but dimpled bedding planes, exhibiting "small hollows and protuberances of a few inches in diameter (cf. Jukes, 1872) are very common. This structure has been termed "current mark" by Kindle (1917), and is said to be due to irregularities in the sand-laden water-currents, or to the impinging of strong currents along sand bars or at other localities. The primary nature of this structure in the Silurian rocks of the Melbourne district, of which there has been some doubt in the past in the minds of Victorian geologists, is clearly indicated by the parallelism of the dimples and swellings in the bedding planes with current-bedding curves within the beds. No examples of oscillation-ripple mark have been observed.

Secondary Structures.

The development of a wrinkled, lobate, or mamillary base to sandstone strata, where these rest upon mudstone layers, is common in the crush zone near Dight's Falls. The structure is best shown where the incompetent beds are thin, and are interbedded as partings betwen the sandstones.

The deformation of the standstones is usually restricted to two or three inches at most at the base of each bed affected, and involves the underlying mudstones. Both sandstones and mudstones, it is clear, were capable of yielding to the deforming forces by flowage, for the wrinkles and lobes on the sandstone bases have smooth surfaces, and bedding planes in them are curved to accommodate themselves to the impressed geometrical forms. The latter, which range from elongated asymmetrical fold-like wrinkles a quarter of an inch or so apart, through rounded linguoid forms, to mammillate knobs, in places show evidence of having been affected by sliding movements between the strata, in the case of the wrinkles and linguoid forms. The mammillate forms, however, and those illustrated in figure 12A, show no clear evidence of movement.

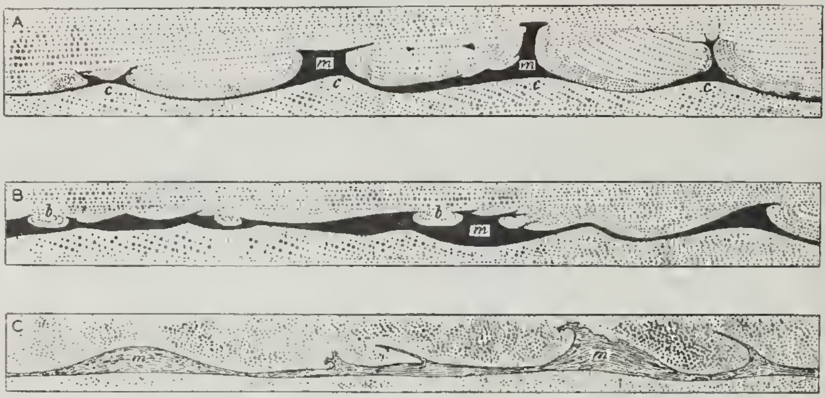


Fig. 12.—Types of mudstone injections into sandstone strata. Mudstone shown by solid black or broken lines, sandstones stippled. *A*, mudstone injections *m* above ripple-crests *c* without evidence of differential bedding plane-slip; *B*, balling up of sandstones at *b*, *b*, and development of wave-like mudstone injections with evidence of slight bedding plane-slip. *C*, mudstone injections above a flat sandstone surface, with evidence of bedding plane-slip. All examples approximately one-third natural size. Dip vertical in the field. Location 10 yards west of *Bythotrephis* bed, Studley Park Road, near Johnston Street Bridge.

The significant data bearing on the origin of these basal sandstone deformations are as follows:—

(1) The structures are developed, so far as was observed, only where sandstones are predominant, e.g., in the crush zone between Dight's Falls and the entrance to the Boulevard.

(2) Not every sandstone stratum exhibits the structures.

(3) The deformation is shown by certain sandy beds that are only 3 inches thick, which are overlain and underlain by mudstones. In these as in all other examples, the top of the affected sandstone stratum remains undisturbed. The structure is, therefore, not due to sub-aqueous gliding, since this would have thrown the strata as a whole into folds, or developed other large or small scale mass deformations.

(4) Where linguoid or wrinkled surfaces are developed, the direction of movement indicated is not constant from bed to bed, and bears no apparent relationship to the major structures.

(5) Nevertheless, close examination of laminated sandstones and of saccharoidal sandstones showing closely spaced stratification planes shows that there has been a very general tendency for the stratification planes to develop minute asymmetrical waves in which the direction of relative motion indicated by the asymmetry of the waves agrees with the rule for folding—the upper bed moves towards the crest of the adjacent anticline.

The interpretation placed upon these facts is as follows:—

(1) For mudstone injections with no indication of differential bedding-plane slip (Type shown in fig. 12A).

In this type, injections of mudstone into the overlying sandstone are restricted to the crests of ripple-marks in the underlying sandstone stratum. Clearly, mudstone from the ripple-troughs flowed towards the crests, where it was forced into the base of the overlying sandstone. This must have occurred when the rocks were subjected to considerable pressure, and not immediately after the deposition of the basal laminae of the upper sandstone, for if the mud was sufficiently tenacious to remain in place during the deposition of this overlying current-bedded sandstone, its viscosity would not have permitted it to rise under the weight of only an inch or two of sandstone above it. Nevertheless, the, sandstone possessed sufficient fluid-plasticity to yield as shown in the diagram. It is suggested that the water expressed from the mudstone during gravitational compaction migrated into the base of the overlying sandstone, while the grains were as yet uncemented, so enabling fluid flow to take place in the lower layers of the sandstone. The mudstone injections were localized at ripple crests owing to the development of components of the vertical compressional forces on the sides of the ripples. In the troughs, the mudstone was subjected to the full compressive force, and it therefore migrated towards the points of least compression, where it was injected into the sandstones in a manner strikingly resembling the experimental salt domes produced by Nettleton (1934). As a result, the basal stratification planes of the sandstones were dragged up along the mudstone injections, producing a mammillate or linguoid surface between the injections.

Further indications that the strata were approximately horizontal at the time of development of the structure are given by the fact that the injections above the ripple-crests are normal to the bedding planes, and that all the injection phenomena are restricted to the lower surfaces of sandstones, even in vertically dipping strata. Had the strata been vertical when the structures developed, the expressed water could have entered the sandstones on both sides of the interbedded mudstones with equal ease, and the mudstone injections would have shown either a definite relationship to tectonic structures, or have risen under isostatic forces, showing a tendency to assume a vertical attitude. It is suggested that an essentially similar process, involving the expression of water from sandstones, its injection into the bases of sandstones causing them to attain fluidal properties, and the injection of sandstone into this fluid sandy mass under the gravitational force due to the load of superincumbent sediments, was involved in the formation of all the mammillate structures that show no evidence of movement.

(2) For mudstone injections into lingoid or wrinkled sandstone bases, indicating movement along bedding planes; also waved stratification planes in laminated sandstones.

Movements along the bedding planes may be either pre-tectonic or tectonic in origin. The former, it is suggested, may be developed as a result of the differential compaction of sands and muds, especially when the strata are markedly lenticular as they are at Studley Park. We may exclude normal sub-aqueous gliding from consideration because all the minor deformations now under discussion are localized within single strata as units. In sub-aqueous gliding groups of strata are affected together. Hadding (1931, pp. 380-1) has expressed the germ of the idea that readjustments along bedding planes may take place during compaction, but he classifies mudstone injections almost identical with those indicating movement along bedding planes at Studley Park and elsewhere in Victoria, as resulting from sub-aqueous sliding. The two phenomena are, however, essentially different. Bedding-plane slip is also developed during tectonic deformation, and when it is remembered that such movements will commence during the early stages of deformation, the difficulty of distinguishing pre-tectonic and tectonic movements will be obvious. So far no criterion has been discovered that might enable a distinction to be drawn, but the virtual restriction of the mudstone injections to the bases of sandstones, and the evidence for great mobility in the latter that the structures afford, strongly suggest that they are pre-tectonic.

It should be realized that this interpretation is of a preliminary nature; further investigations of similar structures in other districts are being carried out. Already, however, it is possible to indicate that, owing to the virtual restriction of the flowage and injection phenomena to the bottom surfaces of sandstone strata, they can be of considerable use in structural mapping. A further result of the present investigations in this connexion is that in thin sandy strata showing current-mark, where the presence of the complete curve of current-bedding greatly restricts the use of current-bedding as an indicator of the order of superposition of inclined strata, the flat base of the current-marked beds, as contrasted with the waved upper surface, can in many cases readily be distinguished.

The occurrence of true sub-aqueous gliding in the Silurian rocks might be suspected from the presence of marked intraformational disturbance in places, but the strong shearing, brecciation, and folding of mudstones and thin sandstones lying between more massive strata, seen on the west face of the cliff at Dight's Falls and in the outlet to the Riley Street drain, are of tectonic origin, as is shown by the development of cleavage in the mudstones at the latter locality, and the slickensiding of adjacent massive strata at Dight's Falls.

Origin of Major Structures.

REVERSE FAULTING.

Although the average strike of the reverse faults is 170°, i.e., making an acute angle with the general trend of the axial lines, it is more significant that the faults in the south of the area (fig. 4A) strike, on the average, parallel to the axial lines in this part, while where the axial lines change their trend in the north, the faults change sympathetically in strike (fig. 4B). It, therefore, appears that the faults and the folds are genetically related. The total vertical distance available for study in the district is, however, so small compared with the magnitude of the major anticlinorium involved that it would be unwise to draw any further conclusions as to the mechanics of formation of the faults in general.

Some examples, however, are of purely local significance. On the north face of the cliff at Dight's Falls, for instance, sandstones and mudstones interbedded between massive sandstones exhibit small-scale incipient imbricate structure with low-angle thrust faults, formed as a result of differential shearing movements of the beds on either side.

FOLDING.

Throughout the district, no significant recrystallization of the Silurian rocks has occurred. So far as could be ascertained without the aid of a universal stage, the quartz grains show no marked preferred orientation, and no strain effects even in folds with a radius of curvature of an inch. The plasticity of the strata was therefore not that of a crystalline material, and the folding must have involved only external grain rotation, slip along sedimentary and tectonically developed S surfaces, and positive and negative dilatation. Certain of the sandstones have also yielded by fracture. The mudstones remained capable of flow throughout the folding and faulting; they filled up the spaces formed by the fracturing of the sandstones, and also flowed into the fold apices between the sandstone strata (fig. 10). The sandstones themselves are thickened at the fold apices, measured examples showing two beds thickening from 2½ inches to 3 inches, one from 3 inches to 3½ inches, and one from 6½ inches to 8 inches. These differences in thickness are most probably due to lateral compression, which would result in thinning of the highly inclined limbs and expansion at the apices, the volume changes being brought about by reduction in the percentage of pore-space, and re-arrangement of the grains. This indicates, in the absence of grain deformation, that the grains were not firmly cemented before folding occurred, and, therefore, that the rocks had not been so deeply buried as to have had their pores closed by compaction and recrystallization, or so impregnated with secondary minerals as to have been cemented by infiltration.